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Large scale pedestrian evacuation modeling framework using volunteered geographical information

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Abstract

With rising instances of extreme events and urban settlements, this paper outlines a pedestrian evacuation modeling framework using volunteered geographical information from OpenStreetMap and simplified queuing-network model to estimate evacuation time, detect bottlenecks and test different evacuation strategies. An example case of a total city wide evacuation is presented for a selection of UK cities with similar total road surface area. Evacuation times are presented for scenarios with and without intervention, where intervention implies that densities on roads are capped to enable maximum flow, highlighting the benefit of rapid evacuation time assessment to benchmark cities.

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1. Introduction

In recent years, the need for large scale evacuation planning tools is becoming increasingly important due to a surge in the number of extreme events as reported by Munich RE (2013). They are occurring more often with intensifying consequences. According to DESA (2013), global population and rapid urbanisation is also on the rise. As a result, rapidly urbanizing regions, especially in Asia, have borne the biggest infrastructure losses suffered anywhere due to extreme events in 2013 than any other time in recent history. Climate change mitigation and call for greater infrastructure resilience are important issues we are still grappling with as species for our long term survival. Given the non-predictable nature of extreme events however, there is an urgent need specifically for preparation tools that can be deployed anywhere world wide immediately after warning signs of extreme events which could help save lives.

Rapid urbanisation presents another problem, the need to keep up with rapidly changing environment. It is vital to depict the environment as accurately as possible for planning. The rise of the internet has mobilized a paradigm shift in how the global environment is surveyed. Something that a highly specialized group of individuals would have

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accomplished over periods of years can now be accomplished collectively and collaboratively over the internet through emerging services like OpenStreetMap (OSM) who gather and distribute volunteered geographical information (VGI).

In the UK, like most developed urban structures, The Civil Contingencies Act 2004 by Walker and Broderick (2006) covers the regulatory framework of emergency planning at different administrative levels. It highlights the cycle of mitigation, preparedness, response and recovery as the sign posts of emergency management. Acknowledging that all considerations are vital, this work fits primarily in the planning stage but as close to the critical time as possible with:

- estimate of evacuation time relative to average departure time during a non-emergency to benchmark a city/region,
- location of likely bottlenecks (e.g. bridges and narrow paths),
- location of endangered areas where other forms of interventions may be required (e.g. helicopters rescue), etc.

Nomenclature

n	Number of agents used in a simulation
w	Assumed standard lane width, 2.5 m/lane
A	Total area of a city road network calculated using total assumed lane widths, km ²
F	Flow of agents, agent/ms
v	Velocity of agents, m/s
ρ	Local link density where the agents are present, agent/m ²

1.1. Related Work

Lämmel et al. (2010b) distinguish between small scale evacuation at building level from large scale evacuation of cities, regions and even countries. The challenge is to adapt tools that have been traditionally used for small scale evacuation to deal with greater number of individuals and interactions, primarily through taking a coarser grain approach while maintaining adequate level of complexity.

It is important to capture more complex behavior in people as it leads to a longer evacuation time and any model that ignores them are too optimistic according to Lämmel et al. (2010b). Examples of these behaviors include herding in dense crowds, ignoring warnings, reuniting with family, not choosing the nearest exit, taking the car despite the chance of congested roads (and adding to congestion), etc.

Jha et al. (2004) developed MITSIM, a macroscopic evacuation simulation environment that uses analogy between traffic and hydrodynamic properties of fluid to perform and estimate complete evacuation time by closing roads and applying security delays at various locations. However, Lämmel et al. (2010b) criticizes models at this level for offering a limited ability to deal with heterogeneous population and complex behavior.

Cellular automata based approach is slightly more versatile in terms of implementing complexity as the macroscopic description emerges from microscopic local interactions.

However, more recently, studies like 'Last-Mile Evacuation' project by Lämmel et al. (2010c) use modified queuing model to simulate pedestrian dynamics using MATSim developed by MATSim Development Team (2008). This study aims to train the inhabitants of the Indonesian city of Padang, a region highly susceptible to tsunamis, after numerically computing the best pedestrian evacuation strategy. It uses detailed satellite imagery and image processing to map the terrain. However, that makes the tool specific to this region, requires a lot of preparation and cannot be applied to new areas that are also vulnerable.

The work described here is an extension of this framework to integrate worldwide VGI from OSM. While it is coarser than aerial imagery, with the community of mappers growing bigger, the quality of the data is only expected to improve as it is scrutinized over time.

2. Method

2.1. Input data

2.1.1. Volunteered Geographical Information (VGI) from OpenStreetMap (OSM)

Haklay and Weber (2008) describe that following the success of Wikipedia, OSM has been operational since 2004 and crowd sources geographical information from its 1.6 million registered users. Neis and Zipf (2012) determined that at least 24,000 users are active contributors.

Since this project aims to utilize a growing wealth of crowdsourced open spatial databases like OSM along with computational mobility and behavioral models to achieve rapid simulation of large-scale evacuation effort in response to major crises, it is important to ensure that the information is accurate. Haklay (2010) compares OSM with Ordnance Survey (OS) data for the UK and finds that the OSM data points, on average, are within 6m of the the position recorded by OS. Other studies present similar results for other countries within Europe.

OSM database is relevant to this paper to describe road networks and administrative boundaries. The roads are classified using 'highway' tag in 'planet.osm.line' database table. This data is used to create network graph for use in the simulation. On the other hand, administrative boundaries are described by 'boundary' tag whose value is 'administrative' in 'planet.osm.polygon' database table. This is useful for performing functions like determining area, masking the roads beyond the edge, etc.

As all roads do not yet have a complete set of metadata like lane width or number of lanes, the total lane width are assumed as shown in Table 1.

Table 1. Total OSM 'highway' tag lane widths where $w = 2.5$ m/lane, an assumed standard lane width. (*All other 'highway' tags.)

OSM tag 'highway'	motorway	trunk	primary	secondary	tertiary	residential	others*
Total assumed lane widths	$3.0w$	$2.0w$	$2.0w$	$1.5w$	$1.0w$	$1.0w$	$0.5w$

The administrative boundaries were selected on the basis of the total network road surface area A within OSM city boundaries in the range of $7.4 < A \text{ km}^2 < 12.6$ calculated using total assumed lane widths in Table 1.

2.1.2. Socio-economic data

To investigate evacuation dynamics, knowledge of population distribution is required. While locally provided regional census data may be more accurate, since one of the objectives is to make the tool deployable worldwide, the search led the to discovery of:

- Global Urban Rural Mapping Project, version 1 (GRUMPv1) year 2000 data which consists of population at a high 30 arc second resolution (approximately 1 km at the equator),
- Gridded Population of the World, version 3, Future Estimates (GPWv3FE) year 2015 data which estimates future population from current trends at a lower 2.5 arc minute resolution (approximately 5 km at the equator).

Balk et al. (2005) explain dataset construction through assimilating worldwide census data, night time satellite imagery and various image processing algorithms. Both are average over 24 hour period and do not capture the peak. The main difference is that the finer resolution data is likely to be out of date, but it has $5\times$ higher resolution.

A more recently released population data called LandScan produced by Bright et al. (2012) is of a higher 30 arc second resolution. However, it is only available at commercial capacity to non-US countries.

As a compromise, the results discussed in this paper use the higher resolution GRUMPv1 year 2000 data scaled up to year 2015 population for the UK conserving the total countrywide population. However, it is assumed that the population distribution has not changed very much. Since it is difficult to predict the exact number of evacuees at the time of initiating an evacuation, by assuming that it generally takes longer to evacuate more people, the upper bound population estimate is expected to conservatively estimate (longer) evacuation time.

In the future, points of interest data within the OSM database is also likely to inform various features of cities that agents are most likely to interact with, such as hospitals for medical attention, schools for shelter, etc.

2.2. Simulation framework

2.2.1. Pedestrian flow dynamics

There is a large variation of flow F agent/ms in empirical measurements of crowd dynamics, a function of density ρ agent/m² and velocity v m/s where $F = \rho \times v$. Johansson (2009) explains that these variations are due to maximum density that can be achieved as a result of variable people size and free speeds that people like to walk at. However, net-time headway, the shortest average gap between people which excludes the radius of their heads, is more or less uniquely constant.

While it is worth paying attention to these regional variations, this model uses a simplified version of Q-model by Lämmel et al. (2010a) as shown in Figure 1 where $v = 1.66$ m/s between $0 \leq \rho$ agent/m² ≤ 1 and linear function $v = (-0.332\rho + 1.992)$ m/s for $1 \leq \rho$ agent/m² ≤ 5.5 . The area under the curve is approximately the same but the linear functions involve fewer steps making them easier and faster to compute. This is a desirable attribute for rapid assessments. Differentiating F with respect to ρ , the maximum flow that can be achieved is $F_{max} = 3$ agent/ms when optimum density $\rho_{opt} = 3$ agent/m².

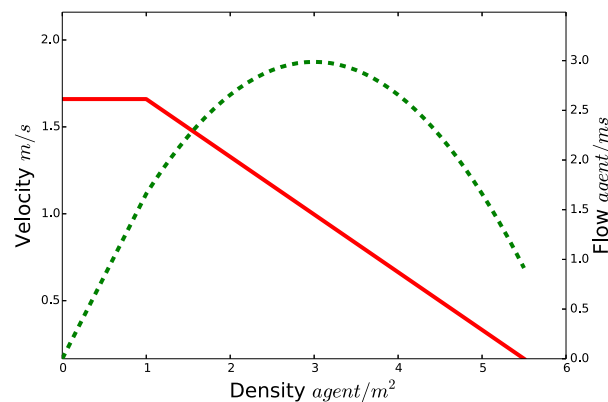


Fig. 1. Simplified queuing-network model based on Q-model by Lämmel et al. (2010a), a fundamental diagram for pedestrians where density ρ agent/m² is given on x-axis, velocity v m/s on y-axis (LHS, red) and flow F agent/ms on y-axis (RHS, dotted green). $v_{max} = 1.66$ m/s, $v_{min} = 0.166$ m/s, $\rho_{max} = 5.5$ agent/m², $F_{max} = 3$ agent/ms where $\rho_{opt} = 3$ agent/m².

It is assumed that the velocity profile for all agents is homogeneous at present although it is to be acknowledged that velocity profile could affect the overall evacuation time since the slowest agents could act as barriers.

Similarly, it is assumed that all agents begin the evacuation process at the same time. However in reality, information takes time to propagate through the population.

2.2.2. Disaster scenarios

Examples of potential applications of this framework include simulation of:

- evacuation to higher grounds during floods where more inputs like elevation data would be required,
- evacuation to open grounds during earthquakes, which could be identified from OSM, which would give an indication of minimum amount of open area available,
- evacuation away from coastal areas/further inland during tsunamis, with the coast acting as a repellant,
- evacuation to designated safe zones during civil unrest, nuclear hazards and other man made disasters (possibly as a radius around the power station),
- total evacuation of regions during region specific threats, etc.

As a point of discussion, this paper focuses on a total evacuation of regions where the agents simply take the nearest exit point. This will consist of three unique combination of cases:

- Case B: Benchmark scenario to determine how long the agents take to reach the nearest exit at free speeds,
- Case N: Evacuation scenario to measure the effect of agent interaction without any intervention,
- Case I: Evacuation scenario with agent interaction and intervention (link densities capped at $\rho_{opt} = 3 \text{ agent/m}^2$).

2.2.3. Network graph simplification

The graph representation of the road network on OSM has chain of edges with many of intermediate nodes between intersections with other roads which define the spatial geometry of the network. While morphological relations between junctions, also known as space syntax as explained by Batty (2004), may influence route choice in reality, the distances to exits are assumed to largely influence the evacuation time ignoring other interaction effects. Hence, the flow through nodes are removed while retaining the intersecting nodes as well as the total length. This makes the simulations run faster as it reduces the number of nodes by a factor of 3.3 ± 0.9 and the number of edges by a factor of 2.8 ± 0.7 , which is significantly less data to process.

2.2.4. Detecting exits

For the total evacuation scenario, it is assumed that the threat is present throughout the selected cities and all the neighboring cities can accommodate all of the evacuees. Therefore, to find the exits, it is also assumed that the major roads are the main routes to other cities (OSM tag 'highway' = 'motorway', 'trunk' and 'primary') and other types of roads with smaller capacities are ignored.

The agents are directed to the nearest leaf nodes (nodes with a single neighbor and an incoming edge) that belong to the major roads. Shortest paths are determined using adapted algorithm by Dijkstra (1959).

Rather than just choosing the nearest exit, a probability of taking an exit proportional to the distance to the exit may be more suitable for a future iteration of the model. This also allows for the possibility of bidirectional intersecting flow since using the current approach does not allow flow intersection.

3. Results

Table 2 shows the range of cities investigated and input parameters: population n and total area of roads in the network with assumed lane widths in Table 1. It also shows ninetieth percentile (90), mean (μ) and standard deviation (σ) of evacuation times for different cases (B, N, I) of total city-wide evacuation. Finally, it shows normalized ninetieth percentile evacuation times $90_{N/B}\%$ and $90_{I/B}\%$.

Table 2. Evacuation times for benchmark (case B), simulation with agent interaction without intervention (case N) and another interactive simulation with intervention (case I). The first two columns are population n and total area of roads A calculated using total assumed lane widths in Table 1. In case B, agents travel at free speed v_{max} to the nearest exit. In case N, there is agent interaction but no intervention. Finally, case I is with both interaction and intervention with density at links not allowed to exceed the optimal 3 agent/m^2 to ensure maximum flow. 90 implies the ninetieth percentile, μ is the mean and σ is the standard deviation of evacuation time. The last 2 columns indicate normalized ninetieth percentile evacuation times $90_{N/B}\%$ and $90_{I/B}\%$. (*Bath & North East Somerset)

OSM admin boundary where $7.4 < A \text{ km}^2 < 12.6$	Simulation parameters $n/1000$ A		Interaction:OFF Intervention:OFF			Interaction:ON Intervention:OFF			Interaction:ON Intervention:ON			Normalized evacuation time	
			90_B	μ_B	σ_B	90_N	μ_N	σ_N	90_I	μ_I	σ_I	$90_{N/B}\%$	$90_{I/B}\%$
B&NES*	186	7.4	86	53	25	92	55	27	88	54	26	106	102
Chichester	117	10.6	106	69	30	121	75	35	109	71	30	114	103
Wakefield	350	10.0	78	47	22	105	58	45	85	50	25	135	108
Stirling Council	78	10.8	119	81	43	167	96	51	124	83	44	140	104
Milton Keynes	201	9.6	127	77	35	181	96	63	135	80	39	143	106
Bradford	531	11.9	96	57	28	235	100	94	117	65	39	246	122
Manchester	486	8.1	37	23	11	103	47	48	57	31	21	281	155
Winchester	175	9.6	120	78	34	384	136	138	163	90	51	319	135
Swansea	140	7.7	211	103	64	681	231	253	282	124	92	323	134
City of Bristol	276	7.4	47	31	13	186	68	78	112	61	88	396	240
Glasgow City	714	12.2	53	34	15	284	116	110	119	58	41	535	224
City of Edinburgh	491	10.8	101	66	27	628	294	263	268	140	104	622	265

Within the range of total area of roads $A \approx 9.7 \pm 1.7 \text{ km}^2$ calculated using assumed lane widths in Table 1, correlation between population n and normalized evacuation times $90_{N/B}\%$ and $90_{I/B}\%$ seems significant ($R = 0.63, 0.58$ and $P = 0.03, 0.05$ respectively) which suggests that with more people, it takes much longer to evacuate.

Bath & North East Somerset (B&NES) displays the lowest $90_{N/B}\%$ and $90_{I/B}\%$ ratio of 105% and 102% indicating that it would not take much longer to evacuate during a crisis than if people were to exit the city at free speed. On the contrary, City of Edinburgh has the highest ratio of 622% and 265% which could be problematic.

It is noteworthy that mean $\sigma_B/\mu_B = 0.48$, $\sigma_N/\mu_N = 0.77$ and $\sigma_I/\mu_I = 0.59$. Greater values indicate a greater spread and vice versa. Interactive case without intervention (case N) has the widest spread of evacuation times.

It is clear that intervention improves evacuation time, most prominently in Swansea ($90_N/90_I \approx 241\%$) and with least difference in B&NES ($90_N/90_I \approx 104\%$) where interactive evacuation times are already close to free speed.

4. Conclusion and Future Work

While there are benefits of using this framework to do rapid evacuation time assessment using OpenStreetMap volunteered geographical information and socio-economical data, the relationship between topological metrics, socio-economical features and evacuation time is still unclear. In the future, the scope of work will be extended to examine:

- effect of different fraction of unusable roads following a disaster,
- extent to which population size is significant and the effect of doubling or halving population size,
- impact of different ratio of vehicle ownership (with different ratio of pedestrians, cars, buses), etc.

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References

- Balk, D., Brickman, M., Anderson, B., Pozzi, F., Yetman, G., 2005. Mapping global urban and rural population distributions. Estimates of future global population distribution to 2015. Environment and Natural Resources Working Papers# 24. New York: United Nations Food and Agriculture Organization/Socioeconomic Data and Ap. Center for International Earth Science Information Network, Columbia University .
- Batty, M., 2004. A new theory of space syntax .
- Bright, E.A., Coleman, P.R., Rose, A.N., Urban, M.L., 2012. LandScan 2012. URL: <http://www.ornl.gov/landscan/>.
- DESA, U., 2013. World Economic and Social Survey 2013. New York: Department for Economic and Social Affairs URL: http://esa.un.org/wpp/documentation/pdf/WPP2012_KEY_FINDINGS.pdf.
- Dijkstra, E.W., 1959. A note on two problems in connexion with graphs. *Numerische mathematik* 1, 269–271.
- Haklay, M., 2010. How good is volunteered geographical information? A comparative study of OpenStreetMap and Ordnance Survey datasets. *Environment and planning. B, Planning & design* 37, 682.
- Haklay, M., Weber, P., 2008. Openstreetmap: User-generated street maps. *Pervasive Computing, IEEE* 7, 12–18. URL: <http://www.openstreetmap.org/>.
- Jha, M., Moore, K., Pashaie, B., 2004. Emergency evacuation planning with microscopic traffic simulation. *Transportation Research Record: Journal of the Transportation Research Board* 1886, 40–48.
- Johansson, A., 2009. Constant-net-time headway as a key mechanism behind pedestrian flow dynamics. *Physical review E* 80, 26120.
- Lämmel, G., Grether, D., Nagel, K., 2010a. The representation and implementation of time-dependent inundation in large-scale microscopic evacuation simulations. *Transportation Research Part C: Emerging Technologies* 18, 84–98. URL: <http://linkinghub.elsevier.com/retrieve/pii/S0968090X09000552>, doi:10.1016/j.trc.2009.04.020.
- Lämmel, G., Rieser, M., Nagel, K., 2010b. Large scale microscopic evacuation simulation. *Pedestrian and Evacuation Dynamics 2008* , 547–553.
- Lämmel, G., Rieser, M., Nagel, K., Taubenböck, H., Strunz, G., Goseberg, N., Schlurmann, T., Klüpfel, H., Setiadi, N., Birkmann, J., 2010c. Emergency Preparedness in the Case of a Tsunami - Evacuation Analysis and Traffic Optimization for the Indonesian City of Padang. *Pedestrian and Evacuation Dynamics 2008* , 171–182.
- MATSim Development Team, 2008. MATSIM-T: Multi-Agent Transportation Simulation Toolkit.
- Munich RE, 2013. Loss events worldwide 2013.
- Neis, P., Zipf, A., 2012. Analyzing the Contributor Activity of a Volunteered Geographic Information Project The Case of OpenStreetMap. *ISPRS International Journal of Geo-Information* 1, 146–165. URL: <http://www.mdpi.com/2220-9964/1/2/146>, doi:10.3390/ijgi1020146.
- Walker, C., Broderick, J., 2006. *The Civil Contingencies Act 2004: risk, resilience, and the law in the UK*. Oxford University Press, USA.